REMARKS

Applicant has carefully reviewed the arguments presented in the Office Action and respectfully request reconsideration of the claims in view of the remarks presented below.

Claims 30, 39 and 41 have been canceled and claims 1, 4, 5, 8-10, 14-18, 31-33, 38, and 40 have been amended. Thus, claims 1-29, 30-38, and 40 are pending in the application.

Rejection to the Drawings

The Examiner indicated that Figure 4 should be designated by a legend such as "Prior Art," because only that which is old is illustrated. Applicants respectfully disagrees and submits that Figure 4 displays the results of the sequence of Figures 3A and 3B.

As indicated in the specification at paragraphs 89-96, the flowchart displayed in Figures 3A and 3B illustrates the sequence of steps which the controller processor of the present invention coordinates during the temperature regulation of a patient (See Paragraph 89). Figure 4 follows Figure 3A and 3B in plotting the fluctuating sensed tissue temperature over a period of time relative to the target temperature and variance set points using a disclosed method of analyzing the sensed temperature data and controlling the heater/cooler of the present invention to change the temperature of a patient's blood (See Paragraph 95).

For these reasons, Applicants respectfully request that the objection to Figure 4 be withdrawn.

Rejections under 35 U.S.C. § 102 (b)

Claims 1-3, 7-9, 38, and 40 were rejected under 35 U.S.C. § 102(b) as being anticipated by WO 00/10494 to Ginsberg et al. (Ginsburg). Applicants respectfully traverse these rejections.

A claim is anticipated by a prior art reference if, and only if, each and every element of the claim is found within the prior art reference. That is not the case here. Applicants have amended claim 1 to more clearly state the steps of the method and to further recite that the method includes analyzing the signals received from the temperature probe while the flow of the heat exchange medium is stopped for a selected period of time and determining an estimated

temperature of the fluid circulating through the lumen of the patient's body from the rate of change of the temperature while the heat exchange medium is stopped. Subsequently, the flow of fluid through the heat transfer catheter is restarted. Furthermore, amended claim 1 recites that the determined temperature is compared to a target temperature and in accordance with the comparison, the heating/cooling apparatus controllably adds or removes thermal energy from the heat exchange fluid to heat or cool the fluid circulating through the lumen of the patient's body.

While Ginsburg discloses a system wherein temperature measurements are made and then provided to a controller to control the heating and cooling of the system, nowhere does Ginsburg teach or suggest a method of stopping flow of fluid to a heat exchanger, analyzing the temperature of fluid circulating through the lumen of the patient's body over a predetermined period of time, during the interruption of fluid flow to a heat catheter, as is claimed in amended claim 1. Ginsburg teaches activating and de-activating the heating/cooling apparatus. However, we respectfully disagree with the Examiner's contention that Ginsburg discloses stopping the flow of fluid through the heat transfer catheter on pg. 43. Nowhere in Ginsburg is there any reference to stopping the flow of heat exchange medium through the heat exchange catheter for a selected period of time. On pg. 43, lines 11-14, Ginsburg discloses activating and deactivating an external device like an "external heating blanket," and not the internal flow of heat exchange medium. Further, Ginsburg does not teach or suggest controllably adding or removing thermal energy from the heat exchange fluid to heat or cool the fluid circulating through the lumen of the patient's body in response to a measurement taken while fluid flow to the heat catheter is stopped, and subsequently restarting the flow of fluid through the heat transfer catheter. Therefore, Applicants submit that Claim 1 is patentable over the art cited by the Examiner.

Claims 2-9 are dependent upon claim 1, and claims 3-5 and 8-9 were amended to ensure correct antecedent basis in view of the amendments made to claim 1. For this reason, the claims include all the limitations of claim 1, and thus Applicants submit that the claims are also novel over the art cited by the Examiner. No new matter was added to any of the amendments made to the claims.

Applicants have amended claim 38 to include the subject matter of claim 39. Claim 38 now recites that the system for regulating the temperature of at least a portion of a patient's body

includes a controller, including a processor and a memory, the processor capable of being programmed by software to sample temperature signals at a predetermined interval, determining a selected temperature value sampled within a selected range of the selected intervals, storing that determined value in a memory of the controller, and incrementing the selected range of selected intervals a selected number of times, and after each increment, repeating determining the selected temperature value sampled within an incremental selected range of selected intervals and store that value and calculate a peak temperature value from the stored determined values with the controller responsive to the calculated peak temperature value to control the heating and cooling apparatus to add or remove thermal energy from a heat exchange medium. None of the art cited, taken alone or in combination, teach or even suggest such a system. While Ginsburg discloses a system wherein temperature measurements are made and then provided to a controller to control the heating and cooling of the system, nowhere does Ginsburg teach or suggest the specific aspects of the invention which include a processor programmed to sample temperature signals at selected intervals and incrementing the selected range of selected intervals a predetermined number of times, and carry out the remaining steps as set forth in amended claim 38.

Additionally, amended claim 38 solves the problem of inaccurate temperature measurement caused by fluctuations in temperature measurements made in a fluid lumen with a patient's body that are caused by the flow of the heat exchange fluid through a heat exchange catheter. Applicants' claimed invention solves this problem by claiming a method which involves programming a processor to sample and analyze the signals provided by the temperature sensors of the probe in such a manner as to determine a peak temperature signal during a specific interval, and to use that peak temperature to compare to a target temperature to then adjust the heating or cooling of the working fluid flowing through the heat exchange catheter. This innovative improvement to the systems disclosed in the cited references solves the fluctuation problem which is not anticipated by the prior art references cited by the Examiner. Accordingly, Applicants respectfully submit that claim 38 is patentable over the cited art and request that it be allowed.

Claim 40 was amended to depend from claim 38, and thus includes all the limitations of that claim. As such, Applicants submit that claim 40 is also novel and not obvious in view of the art cited by the Examiner.

Claim 31 was rejected under 35 U.S.C. § 102(b) as being anticipated by U.S. 6,146,411 to Noda et al. (Noda). Applicants respectfully traverse this rejection.

Applicants have amended claim 31 to recite that a plurality of temperature signals are sampled during a predetermined interval and those temperature signals are analyzed during the predetermined interval to determine a peak temperature. The peak temperature determined is the peak temperature of each of the temperature measurements that occurred during the predetermined interval. At most, Noda discloses temperature measurement and basic feedback in a closed loop to a proportional temperature controller for controlling the cooling or heating to which a fluid of a secondary circuit is subjected. Nowhere does Noda teach nor suggest sampling a plurality of temperature signals during a predetermined selected interval and analyzing the plurality of temperature signals received from a temperature probe during a selected period of time to determine a peak temperature to compare to the target temperature, and controllably adding or removing thermal energy from the heat exchange fluid to heat or cool the fluid circulating through the lumen of the patient's body.

Furthermore, a person having ordinary skill in the art knows that a proportional controller attempts to correct an error between a measured process variable and a desired set-point by calculating and then outputting an algorithm that can adjust the process accordingly. See pg. 1, Appendix I, attached hereto. However, such a person having ordinary skill would not know, reading Noda, to additionally determine a peak temperature over a selected period of time to be used as input to the controller to adjust the heating or cooling temperature of the fluid circulating through the heat exchange catheter, as Applicants' claimed invention does. Applicants' invention claimed in amended claim 31, provides for continuous, real-time temperature feedback to the control system without requiring the flow of the heat exchange fluid to be slowed or stopped to the heat exchanger of the heat exchange catheter, and provides the controller with the capability of detecting sudden changes in patient temperature. The warming or cooling of the patient may continue without interruption in therapy, thus resulting in little or no additional time for the

patient's temperature to reach the target temperature, as is typically required by prior art such as Noda.

Applicants have observed that the measurement of the temperature of blood or other fluid flowing past a heat exchange catheter and temperature probe are influenced significantly by the flow of heating or cooling fluid through the heat exchange catheter. Accordingly, Applicants' claimed invention provides a way to eliminate the measurement inaccuracy due to the flow of heat exchange fluid through the catheter by either, as recited in amended claim 1, stopping the flow of the fluid through the catheter for a selected period of time and allowing the temperature to stabilize, or by analyzing the temperature fluctuations during a selected period of time, as in amended claim 31, and then determining a peak temperature from amongst those fluctuations that is then used as input to the controller to adjust the heating or cooling temperature of the fluid circulating through the heat exchange catheter. In this way, Applicants have improved the measurement process to account for the fluctuation in temperatures due to the flow of heating/cooling fluid through the heat exchange catheter and thus improved the overall accuracy of controlling the system as a whole. None of the disclosures in the prior art cited by the Examiner teach or even suggest the problem solved by Applicants' claimed inventions. For these reasons, Applicants believe that claims 1-3, 7-9, 31, and 38 are patentable over the cited art and respectfully request that the rejections be withdrawn and that claims 1-3, 7-9, 31, and 38, and the claims dependent therefrom be allowed.

Rejections under 35 U.S.C. § 103 (a)

Claims 4-6, 10-13, and 17-28 were rejected under 35 U.S.C. §103(a) as being unpatentable over WO 00/10494 to Ginsburg in view of U.S. 6,969,399 B2 to Schock et al. (Schock). Applicants respectfully traverse these rejections.

This Application and the Ginsburg Patent were, at the time the invention of this application was made, commonly subject to an obligation of assignment to Radiant Medical, Inc. Therefore, the Ginsburg Patent should be disqualified from being used in a rejection under 35 U.S.C. § 103(a) against Applicants' claims. Accordingly, any combination of Ginsburg with Schock is inappropriate.

While Schock teaches the use of a bypass mode that allows a pump apparatus to control the temperature of a liquid, taken alone, the diverter valve and conduit of Schock do not teach the method of claim 1. Schock does not disclose a heat transfer catheter, only an external blanket or sheet-like component. Additionally, nowhere does Schock teach or suggest controlling the interruption of circulating fluid between the heat exchange unit and a heat transfer catheter by diverting the circulating fluid in a diversion pathway, and stopping fluid flow from the heat exchange unit to the heat transfer catheter. Further, nowhere does Schock teach or suggest a method of measuring, monitoring, and analyzing of the temperature over time, or during the interruption of fluid flow to a heat catheter, as is claimed in amended claim 1 and its dependent claims. Accordingly, Applicants respectfully submit that claims 4-6, 10-13, and 17-28 are patentable over Schock, and the rejection should be withdrawn and the claims allowed.

Claims 14-16, 29, and 30 were rejected as being unpatentable over Ginsburg and Schock and further in view of Noda. Applicants respectfully traverse these rejections. As stated above, this Application and the Ginsburg Patent were, at the time the invention of this application was made, commonly subject to an obligation of assignment to Radiant Medical, Inc. Therefore, any combination of Ginsburg and Schock in further view of Noda is inappropriate.

As stated by the Examiner on pg. 11 of the Office Action, Ginsburg in view of Schock does not teach the "further limitations of the controller activating the diverter valve periodically or according to a predetermined time and the controller activating the diverter valve based on the previously determined rate of temperature change." Contrary to the Examiner's position, Noda does not provide the missing limitations. Noda does disclose a temperature measurement and feedback mechanism to a proportional temperature controller for controlling the cooling or heating to which a fluid of a secondary circuit is subjected. However, taken alone or in combination with Schock, one skilled in the art, reading Noda, would not know to additionally activate a diverter valve according to a predetermined time, a predetermined period of time, or a previously determined rate of temperature change. Neither Noda or Schock, alone or in combination, teach or suggest the activation of a diverter valve in accordance with a predetermined time, a predetermined period of time, or a previously determined rate of temperature change, as Applicants claim in claims 14-16. Accordingly, Applicants respectfully

submit that claims 14-16, 29, and 30 are patentable over the cited art, and the rejection should be withdrawn and the claims allowed.

Claims 32-37 were rejected as being unpatentable over Noda. Applicants respectfully traverse these rejections.

In reference to Claims 32-37, the Examiner states on page 14 of the office action, "Noda does not teach the calculating the offset values either statically or dynamically." Applicants disagree that a person having ordinary skill in the art would have known, by reading Noda, that as is described in paragraphs 184 through 199 of Applicants' specification, using the peaks analysis method of the present invention, the controller filters out temperature fluctuations and interpolates a blood temperature that has an offset value that may be calculated from the difference between the interpolated temperature and the actual temperature. In one embodiment disclosed in the present invention, as the interpolated temperature approaches the target temperature, the controller begins to regulate and warm the fluid circulating within the heat exchanger to prevent the patient's temperature from overshooting, or falling below, the target temperature. The offset values may be calculated using linear, logarithmic, or exponential models. The controller of claim 32 is capable of detecting sudden changes in patient temperature and the warming or cooling of the patient may continue without interruption in therapy.

A person having ordinary skill in the art, reading Noda, would not know to controllably regulate the temperature of a patient's body as claimed in claims 32-37 in a way which enables the controller to detect sudden changes in patient temperature without an interruption in therapy, because there is no teaching or suggestion to carry out such a method. Nowhere does Noda teach or suggest a peak temperature analysis that involves analyzing and regulating temperature with the use of a processor programmed to sample a plurality of temperature signals to controllably add or remove thermal energy to a heating/cooling apparatus so that the determined peak temperature occurring during a selected interval approaches the target temperature.

Moreover, the Examiner appears to have engaged in impermissible hindsight reconstruction to opine as to what a person having ordinary skill in the art would know, as there is no teaching or suggestion in Noda of the method of claim 31 or the steps necessary to perform an analysis of the temperature signals, nor is there any other reference cited to support the

Examiner's position. Accordingly, Applicants respectfully submit that claims 32-37 are patentable over the cited art, and the rejection should be withdrawn and the claims allowed.

For all of the foregoing, one skilled in the art would not obtain Applicants' claimed invention from the cited references taken alone or in combination. Thus, Applicants respectfully request that the rejections be withdrawn, and that the pending claims be allowed.

Double Patenting Rejection

Claims 1-6, 7-13, 17-28 and 38 were rejected on the ground of nonstatutory obviousness-type double patenting as being unpatentable over claims 1 and 6 of U.S. Patent No. 6,620,188 B1 in view of U.S. 6,969,699 B2 to Schock et al.

Applicants have prepared and enclosed an executed Terminal Disclaimer with an accompanying Statement Under 37 CFR § 3.73(b) which shows Applicants' common ownership of U.S. Patent No. 6,620,188.

For these reasons, and the reasons set forth above regarding the anticipation and obviousness rejections, Applicants believe that all pending claims are patentable over the cited art. Applicants respectfully request that the claims pending in the application be allowed.

CONCLUSION

Applicants have carefully reviewed the arguments presented in the Office Action and respectfully requests reconsideration of the claims in view of the remarks presented. In light of the above amendments and remarks, Applicants respectfully request that a timely Notice of Allowance be issued in this case.

Should the Examiner have any questions concerning the above amendments and arguments, or any suggestions for further amending the claims to obtain allowance, Applicant requests that the Examiner contact Applicants' attorney, John Fitzgerald, at 310-242-2667.

Please charge any additional fees payable in connection with this Amendment to our Deposit Account No. 06-2425.

Date: June 3, 2009

Respectfully submitted,

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PID controller

Appendix I

From Wikipedia, the free encyclopedia

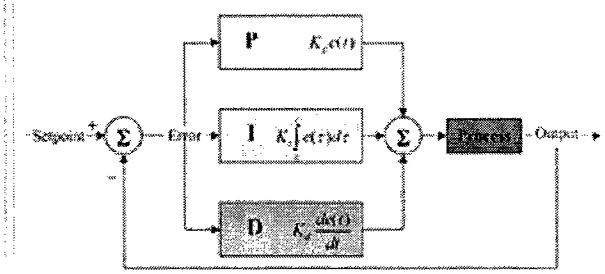
A **proportional–integral–derivative controller (PID controller)** is a generic control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller attempts to correct the error between a measured process variable and a desired setpoint by calculating and then outputting a corrective action that can adjust the process accordingly and rapidly, to keep the error minimal.

Contents

General

The PID controller calculation (algorithm) involves three separate parameters; the proportional, the integral and derivative values. The *proportional* value determines the reaction to the current error, the *integral* value determines the reaction based on the sum of recent errors, and the *derivative* value determines the reaction based on the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the power supply of a heating element.

By tuning the three constants in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the setpoint and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability.



A block diagram of a PID controller

Some applications may require using only one or two modes to provide the appropriate system control. This is achieved by setting the gain of undesired control outputs to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are particularly common, since derivative action is very sensitive to measurement noise, and the absence of an integral value may prevent the system from reaching its target value due to the control action.

Note: Due to the diversity of the field of control theory and application, many naming conventions for the relevant variables are in common use.

Control loop basics

A familiar example of a control loop is the action taken to keep one's shower water at the ideal temperature, which typically involves the mixing of two process streams, cold and hot water. The person feels the water to estimate its temperature. Based on this measurement they perform a control action: use the cold water tap to adjust the process. The person would repeat this input-output control loop, adjusting the hot water flow until the process temperature stabilized at the desired value.

Feeling the water temperature is taking a measurement of the process value or process variable (PV). The desired temperature is called the setpoint (SP). The output from the controller and input to the process (the tap position) is called the manipulated variable (MV). The difference between the measurement and the setpoint is the error (e), too hot or too cold and by how much.

As a controller, one decides roughly how much to change the tap position (MV) after one determines the temperature (PV), and therefore the error. This first estimate is the equivalent of the proportional action of a PID controller. The integral action of a PID controller can be thought of as gradually adjusting the temperature when it is almost right. Derivative action can be thought of as noticing the water temperature is getting hotter or colder, and how fast, anticipating further change and tempering adjustments for a soft landing at the desired temperature (SP).

Making a change that is too large when the error is small is equivalent to a high gain controller and will lead to overshoot. If the controller were to repeatedly make changes that were too large and repeatedly overshoot the target, this control loop would be termed unstable and the output would oscillate around the setpoint in either a constant, growing, or decaying sinusoid. A human would not do this because we are adaptive controllers, learning from the process history, but PID controllers do not have the ability to learn and must be set up correctly. Selecting the correct gains for effective control is known as tuning the controller.

If a controller starts from a stable state at zero error (PV = SP), then further changes by the controller will be in response to changes in other measured or unmeasured inputs to the process that impact on the

process, and hence on the PV. Variables that impact on the process other than the MV are known as disturbances. Generally controllers are used to reject disturbances and/or implement setpoint changes. Changes in feed water temperature constitute a disturbance to the shower process.

In theory, a controller can be used to control any process which has a measurable output (PV), a known ideal value for that output (SP) and an input to the process (MV) that will affect the relevant PV. Controllers are used in industry to regulate temperature, pressure, flow rate, chemical composition, speed and practically every other variable for which a measurement exists. Automobile cruise control is an example of a process which utilizes automated control.

Due to their long history, simplicity, well grounded theory and simple setup and maintenance requirements, PID controllers are the controllers of choice for many of these applications.

PID controller theory

This section describes the parallel or non-interacting form of the PID controller. For other forms please see the Section "Alternative notation and PID forms".

The PID control scheme is named after its three correcting terms, whose sum constitutes the manipulated variable (MV). Hence:

$$\mathrm{MV(t)} = P_{\mathrm{out}} + I_{\mathrm{out}} + D_{\mathrm{out}}$$

where P_{out}, I_{out}, and D_{out} are the contributions to the output from the PID controller from each of the three terms, as defined below.

Proportional term

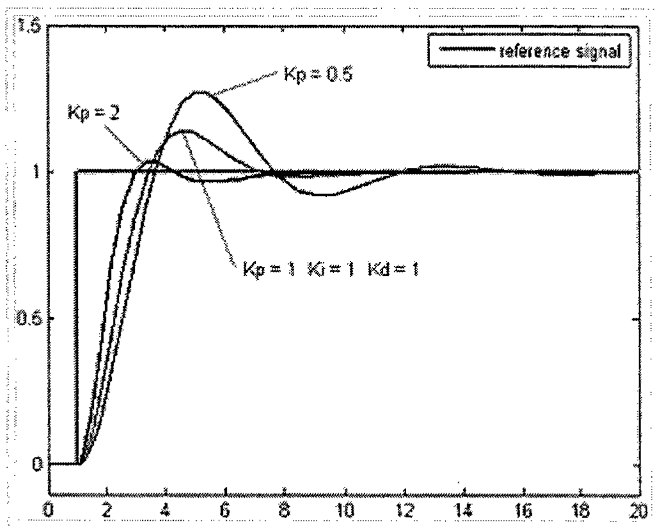
The proportional term (sometimes called *gain*) makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain.

The proportional term is given by:

$$P_{\mathrm{out}} = K_p\, e(t)$$

Where

- P_{out}: Proportional term of output
- K_p: Proportional gain, a tuning parameter
- e: Error $= SP - PV$
- t: Time or instantaneous time (the present)



Plot of PV vs time, for three values of K_p (K_i and K_d held constant)

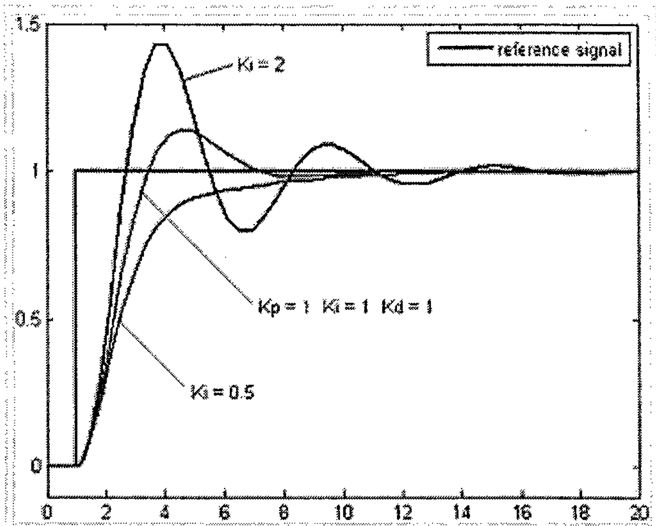
A high proportional gain results in a large change in the output for a given change in the error. If the

proportional gain is too high, the system can become unstable (See the section on loop tuning). In contrast, a small gain results in a small output response to a large input error, and a less responsive (or sensitive) controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances.

In the absence of disturbances, pure proportional control will not settle at its target value, but will retain a steady state error that is a function of the proportional gain and the process gain. Despite the steady-state offset, both tuning theory and industrial practice indicate that it is the proportional term that should contribute the bulk of the output change.

Integral term

The contribution from the integral term (sometimes called *reset*) is proportional to both the magnitude of the error and the duration of the error. Summing the instantaneous error over time (integrating the error) gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain and added to the controller output. The magnitude of the contribution of the integral term to the overall control action is determined by the integral gain, K_i.



Plot of PV vs time, for three values of K_i (K_p and K_d held constant)

The integral term is given by:

$$I_{\mathrm{out}} = K_i \int_0^t e(\tau)\, d\tau$$

Where

- I_{out}: Integral term of output
- K_i: Integral gain, a tuning parameter
- e: Error $= SP - PV$
- t: Time or instantaneous time (the present)
- τ: A dummy integration variable

The integral term (when added to the proportional term) accelerates the movement of the process towards setpoint and eliminates the residual steady-state error that occurs with a proportional only controller. However, since the integral term is responding to accumulated errors from the past, it can cause the present value to overshoot the setpoint value (cross over the setpoint and then create a deviation in the other direction). For further notes regarding integral gain tuning and controller stability, see the section on loop tuning.

Derivative term

The rate of change of the process error is calculated by determining the slope of the error over time (i.e., its first derivative with respect to time) and multiplying this rate of change by the derivative gain K_d. The magnitude of the contribution of the derivative term (sometimes called *rate*) to the overall control action is termed the derivative gain, K_d.

The derivative term is given by:

$$D_{\text{out}} = K_d \frac{de}{dt}(t)$$

Where

- D_{out}: Derivative term of output
- K_d: Derivative gain, a tuning parameter
- e: Error $= SP - PV$
- t: Time or instantaneous time (the present)

The derivative term slows the rate of change of the controller output and this effect is most noticeable close to the controller setpoint. Hence, derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability. However, differentiation of a signal amplifies noise and thus this term in the controller is highly sensitive to noise in the error term, and can cause a process to become unstable if the noise and the derivative gain are sufficiently large.

Summary

The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining $u(t)$ as the controller output, the final form of the PID algorithm is:

$$\mathrm{u(t)} = \mathrm{MV(t)} = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de}{dt}(t)$$

and the tuning parameters are:

Proportional gain, K_p

: larger values typically mean faster response since the larger the error, the larger the Proportional term compensation. An excessively large proportional gain will lead to process instability and oscillation.

Integral gain, K_i

: larger values imply steady state errors are eliminated more quickly. The trade-off is larger overshoot: any negative error integrated during transient response must be integrated away by positive error before we reach steady state.

Derivative gain, K_d

larger values decrease overshoot, but slows down transient response and may lead to instability due to signal noise amplification in the differentiation of the error.

Loop tuning

If the PID controller parameters (the gains of the proportional, integral and derivative terms) are chosen incorrectly, the controlled process input can be unstable, i.e. its output diverges, with or without oscillation, and is limited only by saturation or mechanical breakage. *Tuning* a control loop is the adjustment of its control parameters (gain/proportional band, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response.

The optimum behavior on a process change or setpoint change varies depending on the application. Some processes must not allow an overshoot of the process variable beyond the setpoint if, for example, this would be unsafe. Other processes must minimize the energy expended in reaching a new setpoint. Generally, stability of response (the reverse of instability) is required and the process must not oscillate for any combination of process conditions and setpoints. Some processes have a degree of non-linearity and so parameters that work well at full-load conditions don't work when the process is starting up from no-load. This section describes some traditional manual methods for loop tuning.

There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, then choosing P, I, and D based on the dynamic model parameters. Manual tuning methods can be relatively inefficient.

The choice of method will depend largely on whether or not the loop can be taken "offline" for tuning, and the response time of the system. If the system can be taken offline, the best tuning method often involves subjecting the system to a step change in input, measuring the output as a function of time, and using this response to determine the control parameters.

Choosing a Tuning Method		
Method	**Advantages**	**Disadvantages**
Manual Tuning	No math required. Online method.	Requires experienced personnel.
Ziegler–Nichols	Proven Method. Online method.	Process upset, some trial-and-error, very aggressive tuning.
Software Tools	Consistent tuning. Online or offline method. May include valve and sensor analysis. Allow simulation before downloading.	Some cost and training involved.
Cohen-Coon	Good process models.	Some math. Offline method. Only good for first-order processes.

Manual tuning

If the system must remain online, one tuning method is to first set K_i and K_d values to zero. Increase

the K_p until the output of the loop oscillates, then the K_p should be left set to be approximately half of that value for a "quarter amplitude decay" type response. Then increase K_i until any offset is correct in sufficient time for the process. However, too much K_i will cause instability. Finally, increase K_d, if required, until the loop is acceptably quick to reach its reference after a load disturbance. However, too much K_d will cause excessive response and overshoot. A fast PID loop tuning usually overshoots slightly to reach the setpoint more quickly; however, some systems cannot accept overshoot, in which case an "over-damped" closed-loop system is required, which will require a K_p setting significantly less than half that of the K_p setting causing oscillation.

Effects of *increasing* parameters				
Parameter	**Rise time**	**Overshoot**	**Settling time**	**Error at equilibrium**
K_p	Decrease	Increase	Small change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Indefinite (small decrease or increase) [1]	Decrease	Decrease	None

Ziegler–Nichols method

Another tuning method is formally known as the Ziegler–Nichols method, introduced by John G. Ziegler and Nathaniel B. Nichols. As in the method above, the K_i and K_d gains are first set to zero. The *P* gain is increased until it reaches the critical gain, K_c, at which the output of the loop starts to oscillate. K_c and the oscillation period P_c are used to set the gains as shown:

Ziegler–Nichols method			
Control Type	K_p	K_i	K_d
P	$0.50K_c$	-	-
PI	$0.45K_c$	$1.2K_p / P_c$	-
PID	$0.60K_c$	$2K_p / P_c$	$K_pP_c / 8$

PID tuning software

Most modern industrial facilities no longer tune loops using the manual calculation methods shown above. Instead, PID tuning and loop optimization software are used to ensure consistent results. These software packages will gather the data, develop process models, and suggest optimal tuning. Some software packages can even develop tuning by gathering data from reference changes.

Mathematical PID loop tuning induces an impulse in the system, and then uses the controlled system's frequency response to design the PID loop values. In loops with response times of several minutes, mathematical loop tuning is recommended, because trial and error can literally take days just to find a stable set of loop values. Optimal values are harder to find. Some digital loop controllers offer a self-tuning feature in which very small setpoint changes are sent to the process, allowing the controller itself to calculate optimal tuning values.

Other formulas are available to tune the loop according to different performance criteria.

Modifications to the PID algorithm

The basic PID algorithm presents some challenges in control applications that have been addressed by minor modifications to the PID form.

One common problem resulting from the ideal PID implementations is integral windup. This problem can be addressed by:

- Initializing the controller integral to a desired value
- Increasing the setpoint in a suitable ramp
- Disabling the integral function until the PV has entered the controllable region
- Limiting the time period over which the integral error is calculated
- Preventing the integral term from accumulating above or below pre-determined bounds

Many PID loops control a mechanical device (for example, a valve). Mechanical maintenance can be a major cost and wear leads to control degradation in the form of either stiction or a deadband in the mechanical response to an input signal. The rate of mechanical wear is mainly a function of how often a device is activated to make a change. Where wear is a significant concern, the PID loop may have an output deadband to reduce the frequency of activation of the output (valve). This is accomplished by modifying the controller to hold its output steady if the change would be small (within the defined deadband range). The calculated output must leave the deadband before the actual output will change.

The proportional and derivative terms can produce excessive movement in the output when a system is subjected to an instantaneous step increase in the error, such as a large setpoint change. In the case of the derivative term, this is due to taking the derivative of the error, which is very large in the case of an instantaneous step change. As a result, some PID algorithms incorporate the following modifications:

Derivative of output
: In this case the PID controller measures the derivative of the output quantity, rather than the derivative of the error. The output is always continuous (i.e., never has a step change). For this to be effective, the derivative of the output must have the same sign as the derivative of the error.

Setpoint ramping
: In this modification, the setpoint is gradually moved from its old value to a newly specified value using a linear or first order differential ramp function. This avoids the discontinuity present in a simple step change.

Setpoint weighting
: Setpoint weighting uses different multipliers for the error depending on which element of the controller it is used in. The error in the integral term must be the true control error to avoid steady-state control errors. This affects the controller's setpoint response. These parameters do not affect the response to load disturbances and measurement noise.

Limitations of PID control

While PID controllers are applicable to many control problems, they can perform poorly in some applications.

PID controllers, when used alone, can give poor performance when the PID loop gains must be reduced so that the control system does not overshoot, oscillate or *hunt* about the control setpoint value. The control system performance can be improved by combining the feedback (or closed-loop) control of a PID controller with feed-forward (or open-loop) control. Knowledge about the system (such as the desired acceleration and inertia) can be fed forward and combined with the PID output to improve the overall system performance. The feed-forward value alone can often provide the major portion of the controller output. The PID controller can then be used primarily to respond to whatever difference or *error* remains between the setpoint (SP) and the actual value of the process variable (PV). Since the feed-forward output is not affected by the process feedback, it can never cause the control system to oscillate, thus improving the system response and stability.

For example, in most motion control systems, in order to accelerate a mechanical load under control, more force or torque is required from the prime mover, motor, or actuator. If a velocity loop PID controller is being used to control the speed of the load and command the force or torque being applied by the prime mover, then it is beneficial to take the instantaneous acceleration desired for the load, scale that value appropriately and add it to the output of the PID velocity loop controller. This means that whenever the load is being accelerated or decelerated, a proportional amount of force is commanded from the prime mover regardless of the feedback value. The PID loop in this situation uses the feedback information to effect any increase or decrease of the combined output in order to reduce the remaining difference between the process setpoint and the feedback value. Working together, the combined open-loop feed-forward controller and closed-loop PID controller can provide a more responsive, stable and reliable control system.

Another problem faced with PID controllers is that they are linear. Thus, performance of PID controllers in non-linear systems (such as HVAC systems) is variable. Often PID controllers are enhanced through methods such as PID gain scheduling or fuzzy logic. Further practical application issues can arise from instrumentation connected to the controller. A high enough sampling rate, measurement precision, and measurement accuracy are required to achieve adequate control performance.

A problem with the Derivative term is that small amounts of measurement or process noise can cause large amounts of change in the output. It is often helpful to filter the measurements with a low-pass filter in order to remove higher-frequency noise components. However, low-pass filtering and derivative control can cancel each other out, so reducing noise by instrumentation means is a much better choice. Alternatively, the differential band can be turned off in many systems with little loss of control. This is equivalent to using the PID controller as a *PI* controller.

Cascade control

One distinctive advantage of PID controllers is that two PID controllers can be used together to yield better dynamic performance. This is called cascaded PID control. In cascade control there are two PIDs arranged with one PID controlling the set point of another. A PID controller acts as outer loop controller, which controls the primary physical parameter, such as fluid level or velocity. The other controller acts as inner loop controller, which reads the output of outer loop controller as set point, usually controlling a more rapid changing parameter, flowrate or acceleration. It can be mathematically

proven that the working frequency of the controller is increased and the time constant of the object is reduced by using cascaded PID controller.

Physical implementation of PID control

In the early history of automatic process control the PID controller was implemented as a mechanical device. These mechanical controllers used a lever, spring and a mass and were often energized by compressed air. These pneumatic controllers were once the industry standard.

Electronic analog controllers can be made from a solid-state or tube amplifier, a capacitor and a resistance. Electronic analog PID control loops were often found within more complex electronic systems, for example, the head positioning of a disk drive, the power conditioning of a power supply, or even the movement-detection circuit of a modern seismometer. Nowadays, electronic controllers have largely been replaced by digital controllers implemented with microcontrollers or FPGAs.

Most modern PID controllers in industry are implemented in programmable logic controllers (PLCs) or as a panel-mounted digital controller. Software implementations have the advantages that they are relatively cheap and are flexible with respect to the implementation of the PID algorithm.

Alternative nomenclature and PID forms

Pseudocode

Here is a simple software loop that implements the PID algorithm:

```
previous_error = 0
integral = 0
start:
  error = setpoint - actual_position
  integral = integral + error*dt
  derivative = (error - previous_error)/dt
  output = Kp*error + Ki*integral + Kd*derivative
  previous_error = error
  wait(dt)
  goto start
```

Ideal versus standard PID form

The form of the PID controller most often encountered in industry, and the one most relevant to tuning algorithms is the *standard form*. In this form the K_p gain is applied to the I_{out}, and D_{out} terms, yielding:

$$\mathrm{MV(t)} = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau)\, d\tau + T_d \frac{de}{dt}(t) \right)$$

where

T_i is the *integral time*

T_d is the *derivative time*

In the ideal parallel form, shown in the controller theory section

$$\mathrm{MV(t)} = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de}{dt}(t)$$

the gain parameters are related to the parameters of the standard form through $K_i = \frac{K_p}{T_i}$ and $K_d = K_p T_d$. This parallel form, where the parameters are treated as simple gains, is the most general and flexible form. However, it is also the form where the parameters have the least physical interpretation and is generally reserved for theoretical treatment of the PID controller. The standard form, despite being slightly more complex mathematically, is more common in industry.

Laplace form of the PID controller

Sometimes it is useful to write the PID regulator in Laplace transform form:

$$G(s) = K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s}$$

Having the PID controller written in Laplace form and having the transfer function of the controlled system, makes it easy to determine the closed-loop transfer function of the system.

Series/interacting form

Another representation of the PID controller is the series, or *interacting* form

$$G(s) = K_c \frac{(\tau_i s + 1)}{\tau_i s} (\tau_d s + 1)$$

where the parameters are related to the parameters of the standard form through $K_p = K_c \cdot \alpha$, $T_i = \tau_i \cdot \alpha$, and $T_d = \frac{\tau_d}{\alpha}$ with $\alpha = 1 + \frac{\tau_d}{\tau_i}$.

This form essentially consists of a PD and PI controller in series, and it made early (analog) controllers easier to build. When the controllers later became digital, many kept using the interacting form.

See also

- Control Theory
- Feedback
- Instability
- Oscillation
- Oscillation (mathematics)

External links

PID tutorials

- PID Tutorial (http://www.engin.umich.edu/group/ctm/PID/PID.html)
- P.I.D. Without a PhD (http://www.embedded.com/2000/0010/0010feat3.htm): a beginner's guide to PID loop theory with sample programming code
- What's All This P-I-D Stuff, Anyhow? (http://www.elecdesign.com/Articles/ArticleID/6131/6131.html) Article in Electronic Design
- Shows how to build a PID controller with basic electronic components (http://asl.epfl.ch/research/projects/VtolIndoorFlying/rapports/rapportSemStauffer.pdf) (pg. 22)

Simulations

- Free, real-time PID simulator for Windows (http://sourceforge.net/projects/pid-simulator/)
- PID controller using MatLab and Simulink (http://www.sccs.swarthmore.edu/users/06/adem/engin/e58/lab5/)
- PID controller laboratory, Java applets for PID tuning (http://www.pidlab.com/)

Special topics and PID control applications

- Proven Methods and Best Practices for PID Control (http://www.controlguru.com/pages/table.html)
- PID Control Primer (http://www.embedded.com/story/OEG20020726S0044) Article in Embedded Systems Programming

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1. ^ http://saba.kntu.ac.ir/eecd/pcl/download/PIDtutorial.pdf

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